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ABSTRACT

A narrow-slit injection orifice which is used for the screw compressor (mainly for single screw compressor) injection is described in this paper. Different from the traditional injection orifice, the orifice is slit shaped but not circular. Liquid which is injected by the narrow-slit injection orifice appears as a curtain shape so that the heat transfer area is increased. The cooling effect is enhanced and then the efficiency of the compressor is improved. The injected velocity of the orifice is simulated through the CFD software, and then the experiments are carried out. The study verified the accuracy of the simulation results. It will provide a theoretical foundation for the design of the narrow-slit injection orifice used for the screw compressor.

1. INTRODUCTION

Liquid injected screw compressors have been widely used in industry because of its high efficiency, stable performance and so on. While gas is compressed in the screw compressor, a certain amount of liquid with a certain pressure is injected into the compression cavity generally. The liquid contacts with compressed gas directly and it mainly to play a role of cooling and sealing. Usually it needs to spray 8-15L liquid into per cubic meter gas, the volume ratio is about 1:100(Deng and Shu, 1982). In general, the lubricant fluid flows in the loop depend on the pressure difference between the compressor's exhaust pressure and the spray pressure. For large screw compressor, the oil pump is added the circuit. The injected liquid droplets are mixed with the compressed gas. The extremely heat transfer surface absorbs the heat of gas rapidly, so the compression process is similar to the isothermal process. A reduction on the energy consumptions is up to 7% with a positive spray cooling (Li and Jin, 1992). The accuracy requirements for machining of screw rotors are reduced through a sprayed liquid injection technology, also the performance of the compressor is improved.

The main injection parameters have been investigated, such as injection pressure and temperature, liquid flow rate, orifice diameter, position of the injector, etc. Many scholars have studied the injection technology of screw compressor in the world. Stosic *et al.* (1988) presented some results of mathematical modeling of the oil injection into the screw compressor and its influence upon the thermodynamic process of the engine and analyzed the effect of various parameters upon the compressor physical cycle. Pawan J. and Bowman, J. L. (1986) described a mathematical model to calculate the oil-gas heat transfer, assuming that the oil is injected in the form of non-interacting spherical droplets. The model was used to calculate the effect of the heat transfer on compressor performance. N. Seshaiah *et al.*(2007) carried out the mathematical analysis of oil injected twin-screw compressor and effect of some of the compressor operating and design parameters on power and volumetric efficiencies had been analyzed and presented. Li *et al.* (1992) analyzed the effect of oil atomization and its effect on the exhaust gas temperature of single screw compressor. The influence of the main structural parameters of atomizer on lubricant oil atomization effect was analyzed, and the exhaust temperature of single screw compressor without atomization was compared. Finally, it was concluded that the performance of the compressor is improved effectively by the atomization of lubricant.

The section crosses of the injection orifice are all circle, and the liquid is sprayed into compression cavity in a column sharp. Because the injection path is so short, its effect on liquid injection optimization is limited.

2. INJECTION ORIFICE AND ITS POSITION

In the compressor without volume flow rate regulation, the position of injection orifice is on the side of compression gas and in the section of the compressor that volume has been out of the suction port and compression process starts. The lubricant liquid could be injected through a larger spray injection orifice or through a number of smaller orifices, usually it can obtain better performance of compressor by using a number of small injection orifice. In the large and medium sized injection screw refrigeration machine and process compressor, inner-placed volume flow refrigeration valve device is used usually. When the compressor working under different conditions, the working length of the rotor is changed and the inspiratory end position moves to the exhaust end with the slide valve. Generally, the injection orifice is opened in the slide valve in this type of compressor, the injection orifice will move with the slide valve together. So it is ensure that the lubricant liquid is always sprayed after the end of the suction. In order to improve the volumetric efficiency, sometimes the injection orifices are opened in the middle of the compression process for small and high pressure ratio compressor.

In twin-screw compressor, the injection orifice is opened in or near the intersection of two rotor’s tooth addendum circle (Xing, 2000). Liquid holes can be arranged in one or two rows, as shown in Figure 1. It shows the top view and the left view of the casing.

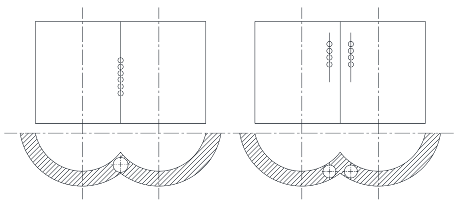

Figure 1: Position and arrangement of the injection orifice

Vertical liquid spray method is currently used in the single screw compressor, that is, the nozzle axis is perpendicular to the surface of the star wheel. The lubricant liquid is sprayed where the star-wheel teeth cutting into the depths of the screw, the liquid injection rate is equal to the circumferential speed of the screw. Another injection method is that lubricant liquid is sprayed into basic capability along the rotation direction of the screw tooth (Yu *et al.* 2012). The orifices are opened in front of projection of the outer edge of the spiral screw that is in front of the star wheel on cylinder when the basic capability is formed. The injection orifice are a pair or many pairs circular holes symmetrical arrangement in two regions of the cylinder， as shown in Figure. 2.

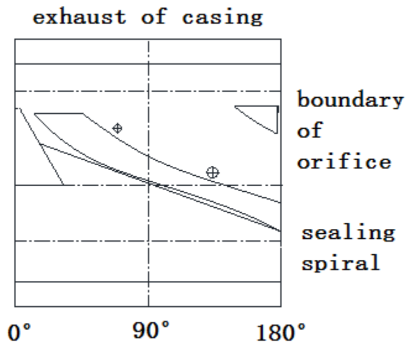

Figure 2: Diagram of the two pairs of injection orifices position

The injection orifices connect to the channel for injection liquid. Liquid channel is arranged on the casing by drilling hole along the axial direction. In part of the compressor, the orifice is opened along the radial of the casing directly.

3. NARROW-SLIT SHARPED INJECTION ORIFICE

Liquid is sprayed into the cogging space in column sharp by the above injection orifice, and the injection path in the cogging is so short. Column sharped liquid is too late to spread for atomization when it attaches to the metal wall of the casing. Therefore, the heat transfer area of the lubricant liquid and the compressed gas is very small. Due to the cooling effect is not ideal, the inner wall of the compression cavity is scaled. Scaling phenomenon is shown in Figure 3. It is a photo for the casing of a brand compressor when the compressor running some time, the cross section of the injection orifice is circular.

Figure 3: Scaling

The heat exchange between the compressed gas and the liquid is less when the size of the injection orifice is larger. That is because the large size of the injection orifice will lead to a lower injection rate and thus format large liquid droplets, heat transfer area decreases. In addition, the increase of liquid droplets will lead to a shorter contact time between compressed gas and lubricant liquid, and the heat transfer effect is weakened more. In order to enhance the heat transfer and promote that the compression process is more similar to isothermal compression of the most power saving theoretically, the lubricant liquid should have a larger surface area in the same amount of liquid. The narrow-slit injection orifice is proposed in this paper. It is opened by arranging appropriate width and length of the narrow slit on the air chamber, and injecting at an appropriate location. The lubricant liquid is sprayed into the cogging space in a curtain shaped, then the span of the lubricant liquid and gas mixed along the axial is larger. And the lubricant liquid in the casing is uniformly distributed in the compression cavity. As a result of the increase of the contact area between the gas and the liquid injection, cooling of the compression process is enhanced. Comparison of the spray effect between a narrow-slit orifice and circular orifice is shown in Figure 4.

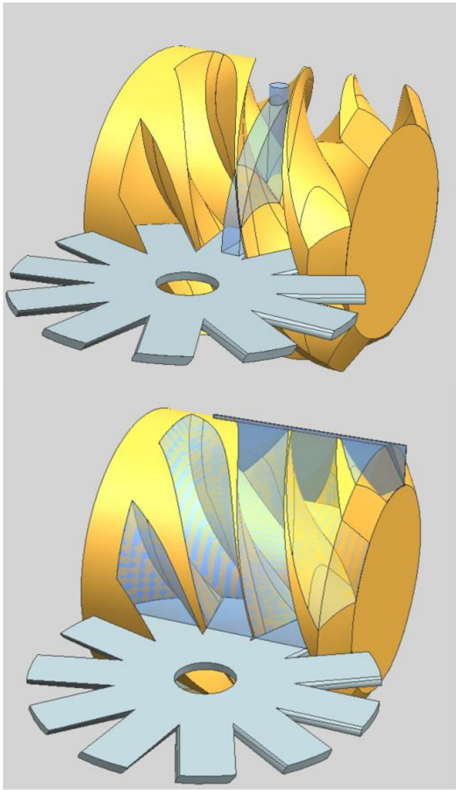

Figure 4: Comparison of liquid injection effects

It is clear that the axial span of lubricant liquid injected by the narrow-slit orifice is larger, and the span of screw groove is more.

In the process of injection, the viscous force of the lubricating liquid and the air resistance and the surface tension of the lubricating liquid play an important role in the crushing of lubricant liquid. Larger liquid droplets that are injected in compression cavity twist under air resistance, and generate friction under the relative velocity of liquid and air. Due to the inner wall of the liquid droplet, a part of the surface protrude out of the liquid droplet is devised and then a smaller liquid drop is formed under the action of the liquid surface tension. At the same time, the liquid droplets will distorted and deformed when the resultant force of surface tension and viscous force is overcome by the air resistance. It continues to that the air resistance and the internal force of the liquid drop regain the equilibrium state. Based on oil atomizing theory, the parameter of Weber number is put forward for evaluating the atomizing level of the oil in compression cavity. The flows of liquid atomization that resulted by different Weber number are divided into five forms (Bein and Hamilton, 1982): liquid drop (We<0.05), smooth liquid flow (0.5<We<5), ripple current (5<We<20), spray flow (We>20).

Weber number is estimated according to Equation (1).

$$W_e = \frac{\rho v^2 l}{\sigma} \tag{1}$$

Where ρ the density of the lubricant liquid, v is the liquid injection rate, l is the characteristic length of the injection orifice, σ is the surface tension coefficient of the lubricant liquid.

The better effect of atomization, the more compressor power consumption is saved. So it's the better that the atomization of the compressor working cavity is the form of spray flow, that is, liquid droplets are fine particles. The liquid droplets of the spray flow are smaller size droplets when Weber number is greater than 20. The compressor which speed is 3000r/min is the main object in reference (Lin *et al.* 2000), the experiment is carried out when the diameter is ϕ3mm、ϕ2mm and ϕ1.6mm. Weber number and the diameter of lubricant liquid drop is 43.4, 60.5, 118.3 and ϕ 3.8mm, ϕ 1.46mm, ϕ 0.75mm according the analysis of experimental data. The atomization of lubricant liquid injected by these three kinds of injection orifice is the spray form through Weber number. However, the diameter of liquid drop is too large when diameter of the injection orifice is ϕ 3.8mm through the drop diameter, quality of atomization is poor. Therefore the Sauter mean diameter (SMD) is introduced, also it is known as surface area mean diameter or Sauter mean diameter. SMD can be estimated by Equation (2).

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$$SMD = 4.52\left(\frac{\sigma_0 \mu_0^2}{\rho_a \Delta p}\right)^{0.25}\left[2.7\left(\frac{d_{or}\,\dot{m}_0 \mu_0}{\rho_a \Delta p}\right)\cos\gamma\right]^{0.25} + 0.39\left(\frac{\rho_0 \mu_0}{\rho_a \Delta p}\right)^{0.25}\left[2.7\left(\frac{d_{or}\,\dot{m}_0 \mu_0}{\rho_a \Delta p}\right)\cos\gamma\right]^{0.75} \tag{2}$$

Where σ_0 is the surface tension coefficient of the lubricant liquid, u_0 is the velocity of the liquid jet, m_0 is the weight of the liquid per diameter range, ρ_0 is the density of the medium around, γ is half cone angle, d_{or} is the diameter of the injection orifice, $\triangle$p is pressure difference of nozzle.

The smaller the SMD value, the better the atomization quality is. Five different types of nozzles under the premise of the same mass flow rate were tested, including three diameter of holes with diameter of ϕ3mm、ϕ2.5mm and ϕ2mm. The Sauter mean diameters of the drops are ϕ3.53mm、ϕ1.97mm、and ϕ0.96mm.

It is concluded that the Sauter mean diameter of droplet will decrease with the decreasing of orifice diameter. Narrow-slit sharped injection orifice can be regarded as a lot of smaller circular injection orifice, and its role is equivalent to an atomizer.

4. INJECTION VELOCITY SIMULATION

The working process of screw compressor is complex, so the model must be assumed and simplified appropriately to receive results quickly in the premise of sufficient accuracy. Simplifications are as follows: 1. Lubricant liquid passage is simplified as a straight pipe; 2. Property of lubricating oil for working medium has not changed; 3. On-way resistance of the lubricant liquid flow process is negligible; 4. The screw cogging is a regular shape.

Steady flow field calculation is achieved by software Ansys 14.0. The grid division is achieved by CFD14.0 ICEM, the results shown in Figure 5:

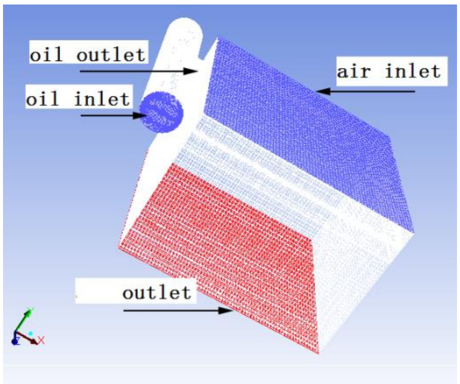

Figure 5: Grid division

The flow control equations are composed of incompressible flow Reynolds equation (3), turbulent kinetic energy equation (κ equation)(4) and the turbulent dissipation rate equation (ε equation)(5).

$$\frac{\partial}{\partial x}\left(\frac{ph^2}{\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{ph^2}{\eta}\frac{\partial p}{\partial y}\right)=6\left(U\frac{\partial ph}{\partial x}+V\frac{\partial ph}{\partial y}+2\frac{\partial ph}{\partial t}\right) \tag{3}$$

$$\rho U_i\frac{\partial k}{\partial x_i}=\mu_t\left(\frac{\partial U_j}{\partial x_i}+\frac{\partial U_i}{\partial x_j}\right)\frac{\partial U_j}{\partial x_i}+\frac{\partial}{\partial x_i}\left\{\left(\mu_t/\sigma_k\right)\frac{\partial k}{\partial x_i}\right\}-\rho\varepsilon \tag{4}$$

$$\rho U_i\frac{\partial \varepsilon}{\partial x_i}=C_{1\varepsilon}\left(\frac{\varepsilon}{k}\right)\mu_t\left(\frac{\partial U_j}{\partial x_i}+\frac{\partial U_i}{\partial x_j}\right)\frac{\partial U_j}{\partial x_i}+\frac{\partial}{\partial x_i}\left\{\left(\mu_t/\sigma_k\right)\frac{\partial k}{\partial x_i}\right\}-C_{2\varepsilon}\rho\left(\frac{\varepsilon^2}{k}\right) \tag{5}$$

Where σ_κ, σ_ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$ are experimental constant.

Firstly, the boundary conditions and the correlation of the model must be set up when the flow distribution of lubricating liquid is simulated by Fluent software. In the model, the setting of boundary at the inlet and outlet of the lubricant liquid is the key to influence whether the flow agree with actual condition of the lubricant liquid. Boundary conditions are set in Table 1.

Table 1: Boundary conditions set

Boundary definition	**Oil inlet**	**Oil outlet**	**Air inlet**	**Outlet**	**Other wall**
Boundary type	Pressure inlet	Interior	Velocity inlet	Pressure outlet	Wall

The simulation result is showed in Figure 6. It is a section of the simulation that liquid oil is injected into the screw cogging in Z axis direction.

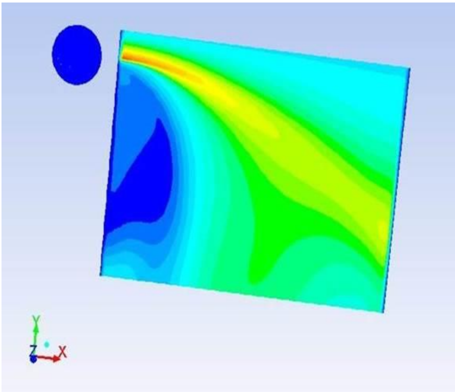

Figure 6 Simulation result

Simulation is carried out when the crack length is 40mm and width is 0.4mm. The injected velocity is shown in Table 2.

Table 2: Simulation results

Pressure(MPa)	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4
Velocity(L/(mm^2 · min))	0.088	0.176	0.247	0.317	0.382	0.441	0.503	0.556

Maximum pressure condition is 0.4MPa because of the limit of the experimental equipment. It is indicated that the injected velocity increases with the increase of pressure in the range of pressure. The simulation results will be verified by experiment.

5. EXPERIMENT EQUIPMENT

Experiment equipment is shown in Figure 7. The experimental oil pump is a gear pump which type is KCB-33.3 with design flow 33.3L/min, pressure 1.45MPa and speed 1420r/min. The oil pump is mainly used for all kinds of machinery and equipment of lubricant system to convey lubricant oil. It is suitable for conveying the lubricating oil which viscosity for $5\times10^{-6}\sim1.5\times10^{-3}m^2/s$ (5-1500cSt) and the temperature under 300° C. The nozzle shape is obtained by machining and low tolerances need to be guaranteed. The accuracy is particularly important because of the small size of the slit. In the experiment, the narrow slit size of the nozzle is 40mm×0.4mm×3mm. The experimental medium is ANDEROL3032M, an ISO32 compressor lubricant formulated from synthetic basefluid utilizing synthetic hydrocarbon (PAO) with specially developed additivesy stems.

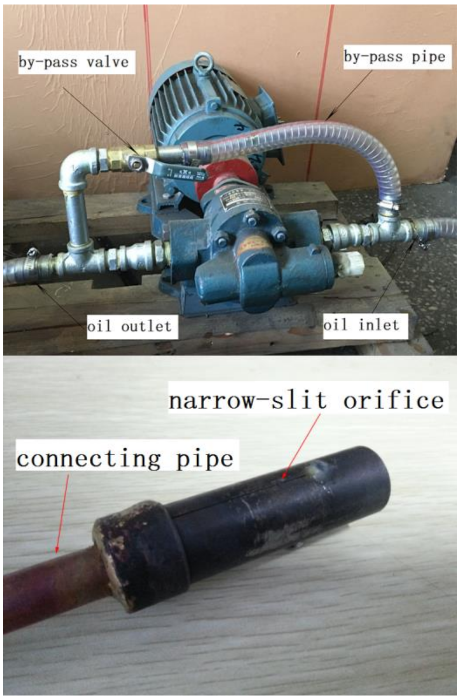

Figure 7: Experiment equipment

The injected velocity obtained by weighing method. Experiment results and errors are shown in Table 3.

Table 3: Experiment results and errors

Pressure(MPa)	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4
Velocity(L/(mm^2 · min))	0.088	0.176	0.247	0.317	0.382	0.441	0.503	0.556
Error (%)	7.7	0.4	1.2	3.6	2.0	2.4	4.0	7.5

Error is the ratio of the difference between simulated results and experiment results to experiment results. It is shown that the simulation results is accordance with the real situation in the experiment because of all errors are less than 10%. The simulation lays a theoretical foundation for the design.

In order to observe the experimental results, the experimental media is water when the simulation of injection flow in the compressor is carried out. When the velocity of air is 35m/s (approximate value of average velocity in the compression chamber), the injection diagram is shown in Figure 8.

Figure 8: Injection diagram

It is shown that the injection is the spray flow. The atomization effect is better. The jet is blown into many small droplets; the heat exchange area increases a lot. The atomizing form is beneficial to the gas-liquid mixture uniformly, and the heat exchange effect is enhanced. It is verified the feasibility of narrow-slit injection orifice.

6 CONSLUSIONS

For screw compressor, the curtain jet that is formed by the narrow-slit orifice proposed in this paper promotes decrease of the heat transfer greatly. Heat transfer between compressed gas and liquid is strengthened so that the compressor temperature decreased. The thermal working process is similar to the isothermal process and the consumption of the compressor is further reduced, the efficiency is improved. And the manufacturing cost can be reduced; its application range is expanded. The comparison between circular injection orifice and narrow-slit injection orifice and the theoretical analysis lay a theoretical foundation for the design and optimization of the narrow-slit injection orifice.

Next the proper size of the narrow-slit injection orifice aiming at a volume model will be designed and the casing will be processed. The real machine experiments will be carried out to test and verify whether the narrow-slit orifice has its superiority.

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